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Effects of liming and fertilization on Collembola in forest soils in relation to soil chemical parameters

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Summary. This study reports the responses of Collembola to liming, at different rates (O, 3 t, 6 t, 12 t/ha dolomite), in combination with P/K-fertilizers in soils from spruce and oak-beech forests in Germany, near Bonn. It concentrates in particular on the influence of varying pH values, and concentrations of mobile nutrients, heavy metals and aluminium in the soil on selected species of Collembola.

In the first two years following treatment the number of species, diversity and dominant species did not show any significant response in the oak-beech forest. In the spruce forest on the other hand the heterogenity of the plots increased following liming and fertilization.

A change in the chemical properties of the soils as a consequence of lime and fertilizer application was perceived in the upper soil layers. The pH values and the contents of mobile nutrients increased in the limed plots and the contents of the mobile heavy metals and aluminium decreased.

Two groups of Collembola showing significant correlations with soil chemical parameters can be distinguished. Abundances of the first group, *Onychiurus furcifer*, *Folsomia quadrioculata* and *Isotoma notabilis* were positively correlated with the concentrations of potassium and, to a certain extent, phosphorus and/or negatively correlated with the contents of heavy metals and aluminium. Abundances of the second group, *Onychiurus quadriocellatus* and *Isotomiella minor*, were negatively correlated with the content of basic cations or the pH value.

In the spruce forest the number of species increased with higher pH and content of K and decreased in the oak-beech forest with increasing content of heavy metals and aluminium.

Key words: Collembola, spruce forest, oak-beech forest, liming, fertilization, chemical parameters of the soil

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Introduction

Over the past twenty years acid deposition has led to changes in soil chemical parameters, e.g. decreasing pH and increasing concentrations of heavy metals and aluminium (Ulrich 1981; Butzke 1984; Brümmer 1987; Veerhoff et al. 1995). In acid forest soils the composition of the fauna has been shown to differ from those in soils with a better supply of basic nutrients (Schaefer 1989). The mesofauna gain increased importance in the process of decomposition because of the low biomass of macrofauna (Graefe 1993). Collembola stimulate the process of mineralisation as well as humification (Herlitzius 1985; Van Amelsvoort et al. 1988).

There are only a small number of studies which describe the relationship between soil chemical parameters and populations of Collembola. Hågvar (1984) and Kopeszki (1992) noted a correlation between pH and the abundances of some Collembola species and Hågvar & Abrahamsen (1984) called for further studies of the influence of soil chemical parameters on selected Collembola species.

This study examines the influence of liming, at different rates, and in association with potassium and phosphorus fertilization on the overall population of Collembola. Furthermore, it outlines correlations between the abundances of selected Collembola species and concentrations of mobile nutrients, heavy metals and aluminium contained in the soils.

Materials and Methods

This study was conducted in the Kottenforst near Bonn (Germany). The test site is located on a plain, 150 m a.s.l. The characteristic vegetation of these sites is oak-beech *(Carpinus betulus-Quercus robur)* and spruce *(Picea abies)*, while stagnic gleysols on loess are typical soil types. In the spruce forest the humus type is moder to raw humus while in the oak-beech forest it is typically mull to moder.

Six plots were chosen in both the oak-beech and spruce forest. Different quantities of lime, partly combined with P/K-fertilization, were applied to these plots. The treatments are shown in Table 1. Each plot was 2500 m^2 in area. The treatment took place mainly in January/February 1994 and partly in 1995. All plots except plot A1 and B1 were also limed in 1988 with 3 t dolomite/ha. Plots A1 and B1 served as references.

Sampling for Collembola and the analysis of the chemical parameters of the soil were carried out in October 1993, prior to the liming and fertilization treatment, and again during the following two autumns. Twelve samples (∅ 0.5 cm) were taken from a square 100 m^2 at the centre of each plot. Collembola were extracted from ten of these before the chemical analysis took place. The soil cores were divided into organic and mineral layers. Only the top 5 cm of the mineral soils was examined for the spruce forest because few Collembola were found in the deeper layers. In the oak-bech forest, where no Oh-horizon was found, the mineral soil was sampled to a depth of 10 cm. The core was divided into two layers each 5 cm in depth.

After the extraction of Collembola, using a modified Berlese-Tullgren extractor, four of the 12 separate samples from each plot and depth were mixed to form one sample. These three mixed samples from each plot and depth were used for the chemical analysis.

NH_4NO_3-extraction (Zeien & Brümmer 1989) was used to determine the content of mobile nutrients, heavy metals and aluminium in the different layers of the soil. Furthermore, the pH value ($CaCl_2$) and the content of organic carbon and total nitrogen were determined by standard methods.

The Spearman coefficient was used to describe correlations between soil chemical parameters and the abundances of selected species of Collembola. Differences in the diversity indices were tested using a randomization test (Solow 1993).

Table 1. Plots under study in the oak-beech and the spruce forest

Treatment	*oak-beech*	*spruce*
1988: not treated 1994: not treated	A1	B1
1988: 3 t/ha dolomite 1994: not treated	A2	B2
1988: 3 t/ha dolomite 1994: 3 t/ha dolomite	A3	B3
1988: 3 t/ha dolomite 1994: 3 t/ha dolomite + PK*	A4	B4
1988: 3 t/ha dolomite 1994: 6 t/ha dolomite + PK*	A5	B5
1988: 3 t/ha dolomite 1994: 6 t/ha dolomite + PK* 1995: 6 t/ha dolomite	A6	B6

* P: 200 kg/ha P_2O_5 (partially acidified rockphosphate), K: 150 kg/ha K_2O (K_2SO_4)

Results

Influence of liming and fertilization on the Collembola population

In all three years the reference plot A1 in the oak-beech forest had significantly lower diversities than the plots which were limed in 1988 (Table 2). In 1995 the positive effect, on diversities, of the second treatment became evident. The diversity of plot A2 was significant lower than some of the plots treated in 1994/95. In 1994/1995, the different lime and fertilizer treatments did not obviously influence the number of species or the diversity in the oak-beech forest plots (Tables 2 and 3).

In the spruce forest plots, the number of species decreased in autumn 1995 (Table 2) but this effect might have been related to climatic factors as it also occurred in the control plots. In 1995 plots B3 and B5 had a significantly lower diversity than the other plots while the highest diversity was found in the untreated, B1, in both 1994 and 1995 (Table 2).

Table 2. Indices of diversity (Shannon-Weaver) and significant differences in the oak-beech (A1–A6) and the spruce forest plots (B1–B6) in autumn 1993 prior to liming and fertilization and in autumn 1994 and 1995 following the treatment

	A1	*A2*	*A3*	*A4*	*A5*	*A6*	*B1*	*B2*	*B3*	*B4*	*B5*	*B6*
1993	2.2	2.4	2.3	2.6	2.6	2.6	2.2	2.5	2.3	2.3	2.4	2.2
1994	2.2	2.7	2.5	2.6	2.4	2.5	2.4	2.5	2.1	2.5	2.3	2.3
1995	2.1	2.3	2.4	2.7	2.6	2.5	2.4	2.2	1.7	2.2	2.0	2.3

Significant differences between the diversities of the different plots ($p < 0.05$)

1993	A1 < A2, A4, A5, A6 A3 < A4, A5, A6	B2 > B1, B3, B4, B6 B5 > B1, B4, B6
1994	A1 < A2, A3, A4, A5, A6 A3 < A2, A4 A4 > A5	B1 > B3, B5, B6 B2 > B1, B3, B5, B6 B3 < B1, B2, B4, B5, B6 B4 > B3, B5, B6
1995	A1 < A2, A3, A4, A5, A6 A2 < A4, A5, A6 A3 < A4	B1 > B2, B3, B4, B5 B3 < B2, B4, B6 B5 < B2, B4, B6

Table 3. Species number of Collembola in the oak-beech plots (A1–A6) and the spruce forest plots (B1–B6) in autumn 1993 prior to liming and fertilization and in autumn 1994 and 1995 following the treatment

	A1	*A2*	*A3*	*A4*	*A5*	*A6*	*B1*	*B2*	*B3*	*B4*	*B5*	*B6*
1993	27	26	23	24	22	33	28	36	29	28	31	31
1994	26	25	31	28	25	24	29	33	25	34	24	28
1995	24	22	20	33	23	27	18	22	21	18	20	24

Ranges of chemical parameters

The minimum and maximum values of the soil parameters, as found in 1993, 1994 and 1995, are shown in Table 4. In autumn 1993 the forest soil was very acidic with pH values ranging from 3.4 to 4.4 in all plots. High concentrations of mobile heavy metals and aluminium were found while there was a severe deficiency of mobile nutrients. The different quantities of lime

Table 4. Minimum and maximum values of pH ($CaCl_2$), mobile nutrients, heavy metals and aluminium in two layers of the soil in the plots in the oak-beech and the spruce forest as found in autumn 1993 prior to liming and fertilization, in autumn 1994 nine months after the treatments and in autumn 1995. 1993: values of the untreated plots A1 and B1, minimum and maximim values for the treated plots A2–A6 and B2–B6, 1994/95: minimum and maximum values for the treated plots (A2–A6 and B2–B6)
(no Oh horizon in B1), (values for contents of elements in mg · kg^{-1})

	oak-beech forest								**spruce forest**							
			1993		*1994*		*1995*				*1993*		*1994*		*1995*	
	layer	**A1**	**min.**	**max.**	**min.**	**max.**	**min.**	**max.**	**layer**	**B1**	**min.**	**max.**	**min.**	**max.**	**min.**	**max.**
pH	**0–5 cm**	3.5	3.5	4.4	4.6	5.4	4.6	5.9	**Oh**		3.4	4.1	4.2	5.5	4.1	6.4
	5–10 cm	3.6	3.6	3.9	3.9	4.7	3.9	4.8	**0–5 cm**	3.1	3.3	3.6	3.3	3.8	3.4	4.1
Na	**0–5 cm**	17.4	14.2	19.5	9.10	15.9	14.0	27.0	**Oh**		43.9	67.4	55.3	88.3	64.9	96.1
	5–10 cm	14.8	12.2	14.8	7.10	12.1	12.0	18.0	**0–5 cm**	27.0	18.0	21.6	9.30	37.4	29.6	48.3
K	**0–5 cm**	103	63.5	133	81.0	445	77.0	172	**Oh**		94.5	152	189	648	205	595
	5–10 cm	56.5	27.5	57.0	42.3	136	42.0	102	**0–5 cm**	113	23.5	94.5	37.9	56.6	49.3	95.3
Ca	**0–5 cm**	149	278	911	1242	1560	1072	1461	**Oh**		672	833	3350	7297	3288	6230
	5–10 cm	51.8	56.3	163	415	974	308	939	**0–5 cm**	533	122	146	220	436	712	1199
Mg	**0–5 cm**	34.3	86.0	300	291	386	231	399	**Oh**		259	989	1012	2577	797	1197
	5–10 cm	15.2	24.5	91.0	96.9	280	83.0	277	**0–5 cm**	55.1	53.9	109	64.8	203	240	302
P	**0–5 cm**	2.09	0.54	2.10	1.24	3.20	0.95	2.25	**Oh**		1.40	2.24	2.16	11.2	5.77	30.3
	5–10 cm	1.04	0.19	1.04	0.87	1.81	0.70	1.36	**0–5 cm**	1.94	0.25	0.43	0.52	1.45	1.15	3.05
Fe	**0–5 cm**	16.7	1.50	6.00	0.02	4.20	0.00	5.56	**Oh**		7.20	32.4	0.02	13.1	0.00	25.1
	5–10 cm	16.6	1.60	4.80	0.02	5.80	0.00	11.3	**0–5 cm**	49.5	24.1	40.0	17.0	52.6	30.7	69.1
Mn	**0–5 cm**	29.7	35.2	73.1	25.2	147	11.0	87.0	**Oh**		44.0	65.5	37.8	75.0	17.9	154
	5–10 cm	9.00	16.0	25.8	32.6	83.9	29.0	80.0	**0–5 cm**	62.7	2.94	5.52	10.5	15.6	22.0	38.0
Pb	**0–5 cm**	7.74	0.59	4.64	0.13	1.81	0.03	0.58	**Oh**		1.90	6.40	0.30	5.40	0.03	2.45
	5–10 cm	5.46	2.40	4.44	0.70	3.95	0.12	4.21	**0–5 cm**	4.63	3.90	6.90	3.10	7.10	3.24	5.12
Cd	**0–5 cm**	0.12	0.04	0.15	0.02	0.17	0.01	0.07	**Oh**		0.07	0.14	0.03	0.13	0.03	0.15
	5–10 cm	0.13	0.04	0.10	0.05	0.20	0.03	0.14	**0–5 cm**	0.14	0.03	0.08	0.05	0.10	0.04	0.08
Al	**0–5 cm**	289	15.8	188	2.50	40.6	2.80	10.3	**Oh**		24.3	179	2.90	125	2.30	15.0
	5–10 cm	281	164	269	30.3	195	7.80	169	**0–5 cm**	286	298	399	231	431	239	297

applied, partly combined with P/K-fertilization had a strong influence on the chemical parameters of the soil. In 1994 the changes were observed particularly in the organic layer, but in 1995 in the oak-beech forest effects were found even at a depth of 10–15 cm. In the treated plots, the pH values and the contents of nutrients such as K, Ca, Mg and P increased, whereas the concentrations of heavy metals and aluminium were reduced. In the fertilized plots the concentrations of P and K increased.

Correlations between mobile elements of the soil and selected Collembola species

The hypothesis was that the abundance of some species of Collembola would be related to the soil chemical parameters. Correlations were calculated separately for each soil depth and for the two forest types including the values for all six plots. The results given here only reflect those cases where a significant correlation (Spearman) was found between the soil chemical parameters and the abundances of Collembola and where non significant correlations confirmed the same trends at a different soil depth and in a different year. There was a large variation in the soil chemical parameters which means that significant correlations cannot always be found at different soil layers and in different years when Collembola species show a non linear relation to these soil parameters.

In the oak-beech forest two groups of Collembola were found showing different reactions to soil chemical parameters (Table 5). The abundances of the first group, which consisted of

Table 5. Correlations (Spearman coefficients) between the pH ($CaCl_2$) values, mobile nutrients, heavy metals, aluminium and the abundances of selected species of Collembola in the Ah horizon (0–5 and 5–10 cm) of the oak-beech plots in autumn 1993 prior to liming and fertilization and in autumn 1994 and 1995. (n = 6 for each depth and date), values < 0,2 are not noted in the table, (* = p < 0,05; ** = p < 0,01; *** = p < 0,001)

		1993		**1994**		**1995**	
		0–5 cm	*5–10 cm*	*0–5 cm*	*5–10 cm*	*0–5 cm*	*5–10 cm*
Mesaphorura macrochaeta	Al	**0.78***	0.30	0.31		0.20	
Onychiurus furcifer	K	**0.82***	0.40	0.37	0.46	0.67	
	Mn	**–0.93****	–0.65		–0.21	–0.75	**–0.84***
Onychiurus quadriocellatus	pH	**–0.84***	–0.55	–0.64		–0.40	
	Fe	**0.84***	0.46	**0.89***	0.43	0.49	
	Pb	**0.84***	0.64	0.63		0.49	
	Al	**0.84***	0.63	0.63		**0.87***	
	$C_{org.}$	**0.81***	0.67	**0.81***		**0.88***	
	$N_{tot.}$	0.66	0.67	**0.92****		**0.89***	
Folsomia quadrioculata	K	**0.93****	0.37	0.77	0.46	0.66	
	P	**0.93****	0.26	**0.94****		0.43	
	$C_{org.}$		**0.84***	0.37		0.48	
	$N_{tot.}$		**0.84***	**0.88***		0.20	
Isotoma notabilis	Mn	**–0,88***		–0.48	–0.76		**–0.41**
	Cd	–0.31	–0.26	–0.55	**–0.92****		
Isotomiella minor	Ca	**–0.88***	–0.71			–0.43	
Species number	Mn	**–0.82***	–0.25	–0.40	–0.54	–0.71	–0.70
	Cd	**–0.88***	–0.40	–0.47	**–0.81***	–0.76	–0.45
	$C_{org.}$	**0.90***			0.3	0.31	

Onychiurus furcifer Börner, *Folsomia quadrioculata* Tullberg and *Isotoma notabilis* Schäffer were positively correlated with the concentrations of potassium and, in part phosphorus, and/or negatively with the content of the heavy metals manganese and cadmium. The concentrations of the trace element manganese in the mobile fraction are higher in these very acidic soils than those of sodium and not much lower than those of potassium and aluminium (Table 4). Therefore, a possible effect of manganese has to be considered.

The second group *Mesaphorura macrochaeta* Rusek, *Onychiurus quadriocellatus* Gisin and *Isotomiella minor* Schäffer, may be characterised as acidophile species. Their abundances were negatively correlated with the content of calcium (*I. minor*), pH (*O. quadriocellatus*) and positively with contents of mobile Fe, Pb or Al (*M. macrochaeta*, *O. quadriocellatus*). Furthermore, the species *F. quadrioculata* and *O. quadriocellatus* from the two groups were positively influenced by the content of $C_{org.}$ and $N_{tot.}$. The species richness showed a negative correlation with the concentrations of the heavy metals manganese and cadmium.

In the spruce forest abundances of *O. furcifer* and *F. quadrioculata* decreased with increasing contents of heavy metals (Fe, Mn, Pb, Cd) and in part aluminium. *Friesea mirabilis* (Tullberg) showed a positive correlation with the content of Na (Table 6).

Isotoma notabilis was negatively correlated with the content of phosphorus, a phenomenon which was not confirmed by the correlations for the oak-beech forest and may be accidental. The number of species in the spruce forest increased with pH and the content of potassium and in the oak-beech forest it decreased with increasing content of potentially toxic elements (Mn, Cd). The total abundance of Collembola in the spruce forest decreased with increasing content of iron (Table 6).

Table 6. Correlations (Spearman coefficients) between the pH ($CaCl_2$) values, mobile nutrients, heavy metals, aluminium and the abundances of selected species of Collembola in the Oh horizon and in the Ah horizon (0–5 cm) of the spruce forest plots in autumn 1993 prior to liming and fertilization and in autumn 1994 and 1995. (n = 6 for each depth and date), values < 0,2 are not noted in the table, (* = p < 0,05; ** = p < 0,01; *** = p < 0,001)

		1993		1994		1995	
		Oh	*0–5 cm*	*Oh*	*0–5 cm*	*Oh*	*0–5 cm*
Friesea mirabilis	Na	**0.90****	0.60	0.60	0.75	**0.90***	**0.88***
Onychiurus furcifer	Ca	0.20	**0.81***	0.33		0.35	
	Fe	**–0.97****	–0.30	**–0.86***		–0.35	
	Mn	**–0.93****	–0.46			–0.70	
	Pb	**–0.90****	–0.23	–0.33		–0.35	
	Cd	**–0.92****	–0.46			–0.70	
Folsomia quadrioculata	K	0.60	0.37	**0.97****		0.30	
	Pb	–0.50		**–0.87***	0.43		
	Cd	–0.41	0.43	**–0.87***	–0.49	–0.60	
	Al	–0.60		**–0.87***		–0.60	
Isotoma notabilis	P	**–0.83***	–0.70	–0.41			
Species number	pH	**0.90****			0.36	0.67	
	K	**0.90****	**0.84***	0.30		0.67	
	Fe	–0.70	–0.50	**–0.87***			–0.38
	Al	**–0.90****	–0.23	–0.30	–0.39	–0.83	
Abundances of all Collembola	Fe	**–0.90****	–0.77	**–0.87***		0.50	–0.77

Discussion

The relationship between soil chemical parameters and the abundances of selected species of Collembola is complex. Competition between the different species of Collembola as well as the correlations between pH values and the contents of the nutrients, heavy metals and aluminium have to be taken into consideration (Hornburg & Brümmer 1993). Also the reaction of the microflora, the main food of Collembola, has to be considered (Bååth et al. 1980). This study concentrates on the influence of the chemical parameters on the Collembola. Whether or not the correlations described are based on direct or indirect effects will require further research.

Hartmann et al. (1989) reported a negative influence of liming and fertilization on the diversity of the Collembola in a spruce forest. In this study a reduced diversity only occurred after the second treatment on the plots B3 and B5. Other treated plots did not show this effect. Nevertheless in 1994 and 1995 the highest diversity was found in the reference plot B1.

Bengtsson & Rundgren (1988) showed that heavy metals (Zn, Cu, Pb), in very high concentrations due to emissions, have a negative effect on the number of Collembola species. This study suggests that there is also a negative correlation with other mobile heavy metals (Cd, Mn). In particular manganese seems to be important in the forest soils investigated. The conclusion to be drawn from this is that increasing acidification with all its consequences, such as higher concentrations of heavy metals including aluminium and loss of nutrients leads to decreased numbers of Collembola species.

The pH value did not seem to be the most important parameter influencing the abundances of some species. While it characterises the chemical situation of the soil, the most important factors in acid forest soils seemed to be mobile heavy metals, nutrients and Al. The pH value, for example, did not correlate with the abundance of *I. notabilis* but the concentrations of heavy metals did. Hågvar & Abrahamsen (1984) indicated that the abundances of these species were not influenced by pH if values are around four. Under these conditions other factors have a limiting effect on the population.

Fritsch (1993) showed that *I. minor* occurred preferencially in the acid area near the stems of trees, thus confirming the results of this study which showed that there is a negative correlation between the abundances of *I. minor* and the content of calcium (Table 6). Fritsch (1993) also described decreasing abundances of *F. quadrioculata* and *O. quadriocellatus* in the acid area near the stem of trees which again confirms the results found in this study (Table 6). Hartmann et al. (1989) showed that liming had a positive effect on the abundances of *F. quadrioculata*. This phenomenon may be caused by decreasing contents in heavy metals and aluminium.

Further investigations will show whether the Collembola species tested can be seen as indicator species and which correlations are based on direct or indirect effects.

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